

Lab – 1: Linear Solenoid Actuator

1 Objectives

The goal of this experiment is to study the principles of electromechanical energy conversion in a typical linear solenoid. For a given sample solenoid, both the inductance and the force will be measured as a function of the plunger position. Based on the measured data, the students will develop a mathematical approximation (model) of the solenoid and then use this model to predict and verify the force-position characteristics.

2 Pre-Lab

Read the corresponding chapter in the textbook as well as review the class notes and this Manual. For the solenoid depicted in Figure 1, derive the equations (1) and (2). Show your Pre-Lab to your TA and let him sign/date it. You will have to include the signed pre-lab page with your lab report.

3 Background

A solenoid is a simple linear actuator that uses a principle of position-dependent reluctance to convert electrical energy into a mechanical energy of the plunger movement which is then used to apply force. The cross-sectional view of a typical solenoid is shown in Figure 1.

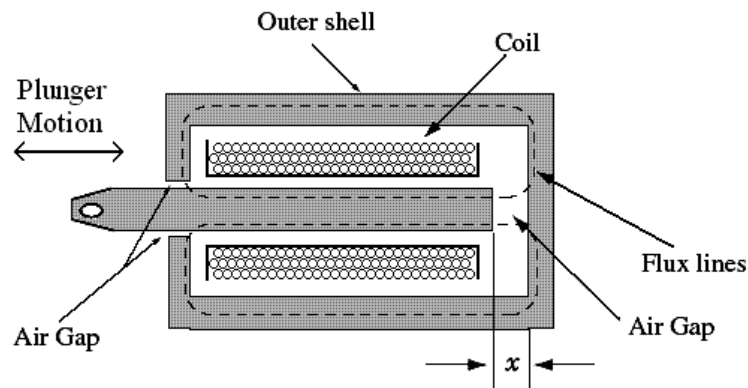


Figure 1: Cross-section of a solenoid. Dashed lines show magnetic flux.

The magnetic path encountered by the flux consists of the outer shell, the plunger, and the front and back air-gaps. Because the back air-gap is determined by the plunger position, the overall effective reluctance is position-dependent. Therefore, the total flux flowing through the magnetic circuit depends on the applied **magneto-motive force mmf** (ampere-turn product) as well as the position of the plunger. In the pre-lab, you will show that the solenoid's inductance can be approximated as

$$L = \frac{k_1}{k_2 + x} + L_o \quad (1)$$

where the parameters k_1 and k_2 depend on geometry, materials, and winding making up the device. Here L_0 represents the effective leakage inductance or the inductance with the plunger completely removed, and x is the plunger position or the back air-gap. You will also show that once these parameters are found, the plunger force for a given position x and current I can be approximated and/or predicted by the following equation

$$F_{e,calc} = \frac{-k_1 I^2}{2(k_2 + x)^2} \quad (2)$$

4 Experiment Apparatus

The solenoid experiments are controlled by a PC equipped with a **Data Acquisition (DAQ)** Card using the LabView software and the NI ELVIS National Instruments Canada module as shown in Figure 2. A power amplifier (see Figure 3) has been interfaced with the NI ELVIS module and the DAQ card so that output signals of up to 10 V and 400 mA can be generated to drive the solenoids directly.

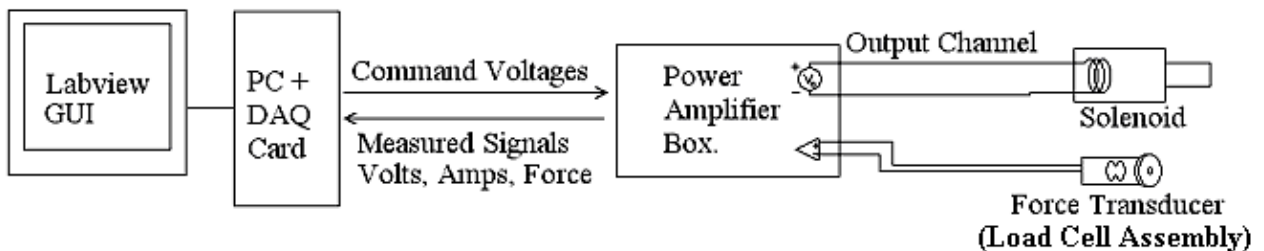
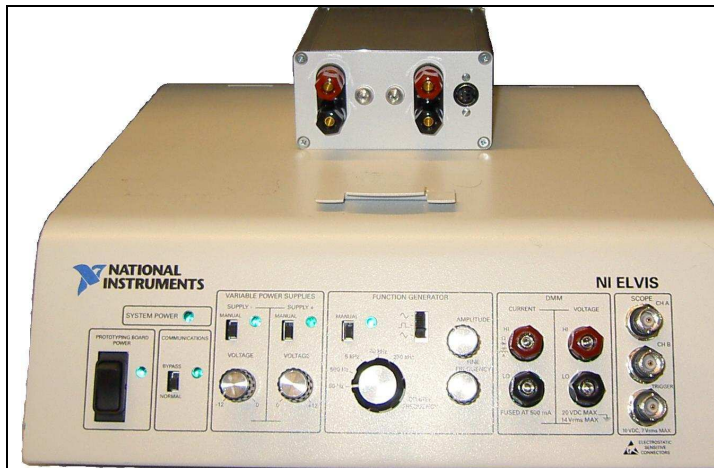


Figure 2: Block diagram of Lab Components

This lab requires the following components:

	<p>Solenoid Bench: This bench is equipped with a linear DC Solenoid, a Load Cell Assembly for measuring the force, and a Lever Arm for pulling the solenoid plunger.</p>
	<p>Power Amplifier Box: This box contains two controllable Linear Power Amplifiers (channel A and B) capable of delivering output up to ± 10 V at 400 mA. The output of each channel is controlled through the LabView interface. There is also additional input for the Load Cell for measuring the force.</p>



NI ELVIS Box: The Measurement Box must be plugged into the National Instrument unit (NI ELVIS), which in turn connects to the Data Acquisition (DAQ) card inside the PC. Make sure that the power switch on the back of NI ELVIS Box is turned on, and that the switch on its front panel left side is also turned on.



Calibration Weights: These weights are used to calibrate the Load Cell so that the measured voltage can be converted to the force.

4.1 Power Amplifier

The amplifier box contains two controllable medium current output channels capable of delivering ± 10 V at 400 mA, one of which will be used to power the solenoid. Linear amplifier is used to avoid the switching noise present with the PWM switching power amplifiers. A bi-colour LED is used as a visual indicator of the output voltage, turning red at positive voltages and blue under negative outputs.

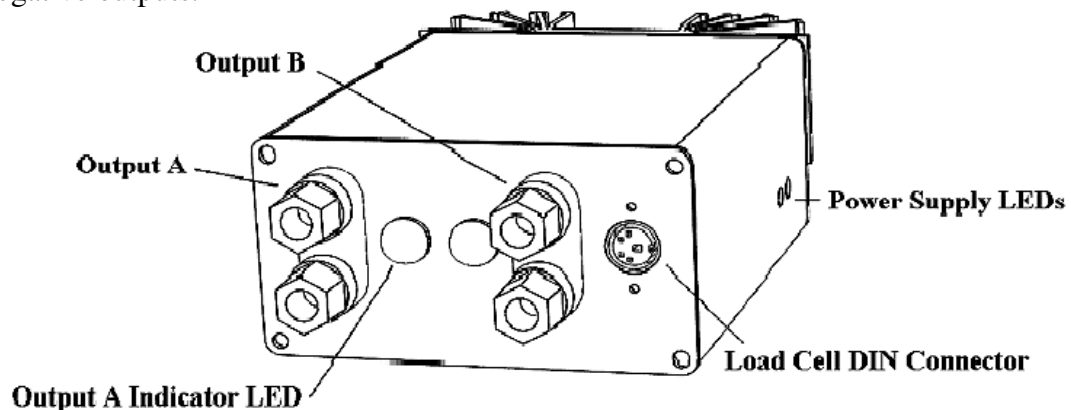


Figure 3: Power Amplifier Box. Only the output channel A is used in this lab.

The DIN connector attaches to a strain gauge force transducer (see the load-cell on Figure 6). It provides an excitation voltage to the sensor and amplifies the resulting force signals. Internally, the power amplifier also senses the current flowing out of each channel. This information is

transmitted, along with the voltage and force signals, back to the DAQ card and then to a PC for analysis.

4.2 Solenoid Bench Components

The Solenoid Bench depicted in Figure 4 permits measuring the inductance and pulling force of a Solenoid at various plunger depths (positions). The bench includes: a linear Solenoid mounted with Inside Micrometer; a String connecting the plunger with the Lever Arm; and a Load Cell Assembly to measure the force. The plunger position is adjusted by the Micrometer and the external force is applied by pulling the Lever Arm.

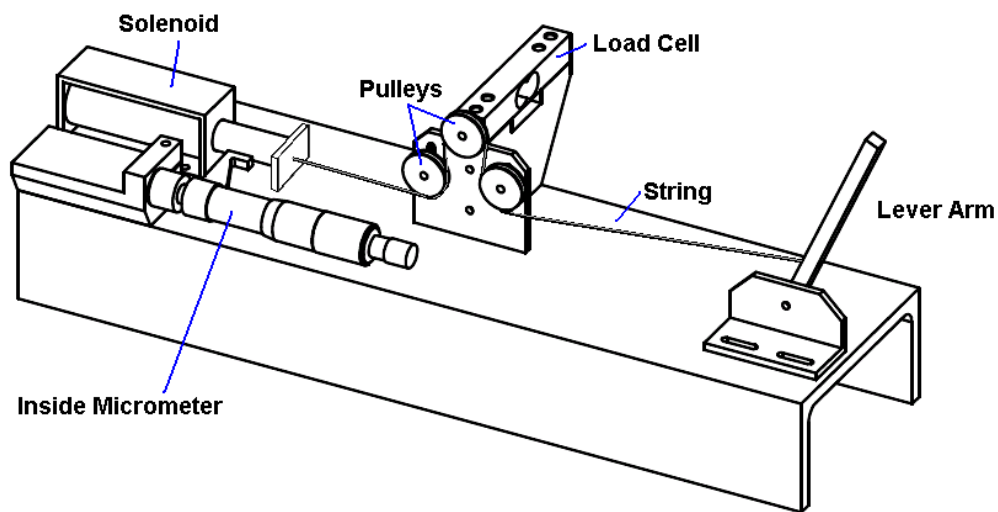


Figure 4: Detailed diagram of the Solenoid Bench

4.2.1 Load Cell Assembly – Force Transducer

The solenoid plunger is attached to a string as depicted in Figure 4 and 5. The details of the Pulleys assembly are shown in Figure 5. The pulling force F is determined from the tension in the string. In the given arrangement, the downward force on the load cell is twice the solenoid pulling force. To measure this force, the load cell has strain gauges glued to the metal surfaces. The wire resistances form a bridge network shown in Figure 6. A force causes the metal to flex, which stretches and compresses the wires of a bridge network shown in Figure 6. Thus, deformation of the flexing surfaces increases the resistance of the wires in tension and decreases the resistance of those in compression. Therefore, the bridge output voltage varies linearly with the change in resistance ΔR , which is proportional to the force.

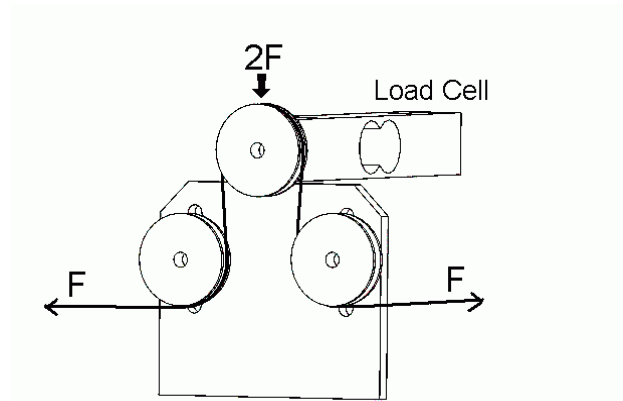


Figure 5: Pulleys assembly on the Load Cell

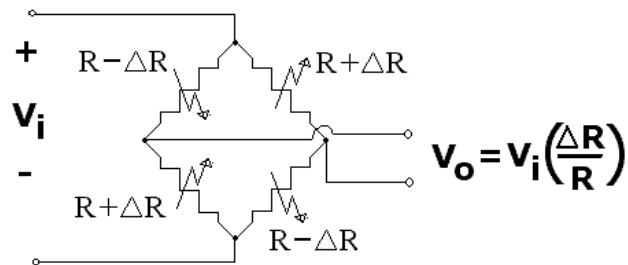


Figure 6: Strain gauge bridge (flex causes resistance change of ΔR .)

4.2.2 Solenoid Micrometer

The solenoid experiments require precise and reproducible control of the plunger position. The solenoid characteristics are sensitive to position and movements as small as 10 microns which can cause a noticeable change in the measurements. A high degree of spatial positioning is achieved by using a machinist micrometer to set the plunger position as depicted in Figure 7. The micrometer handle is turned to set the plunger's stop position.

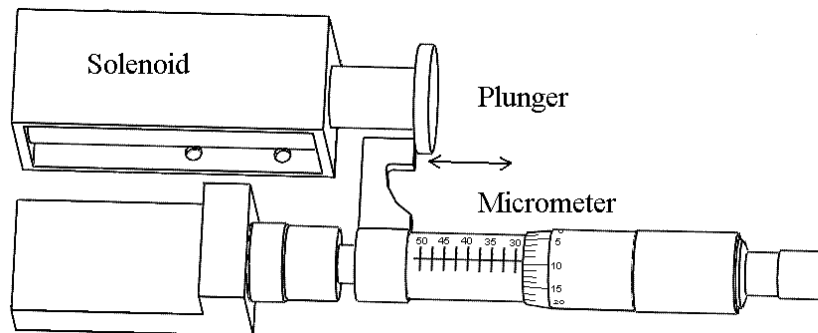
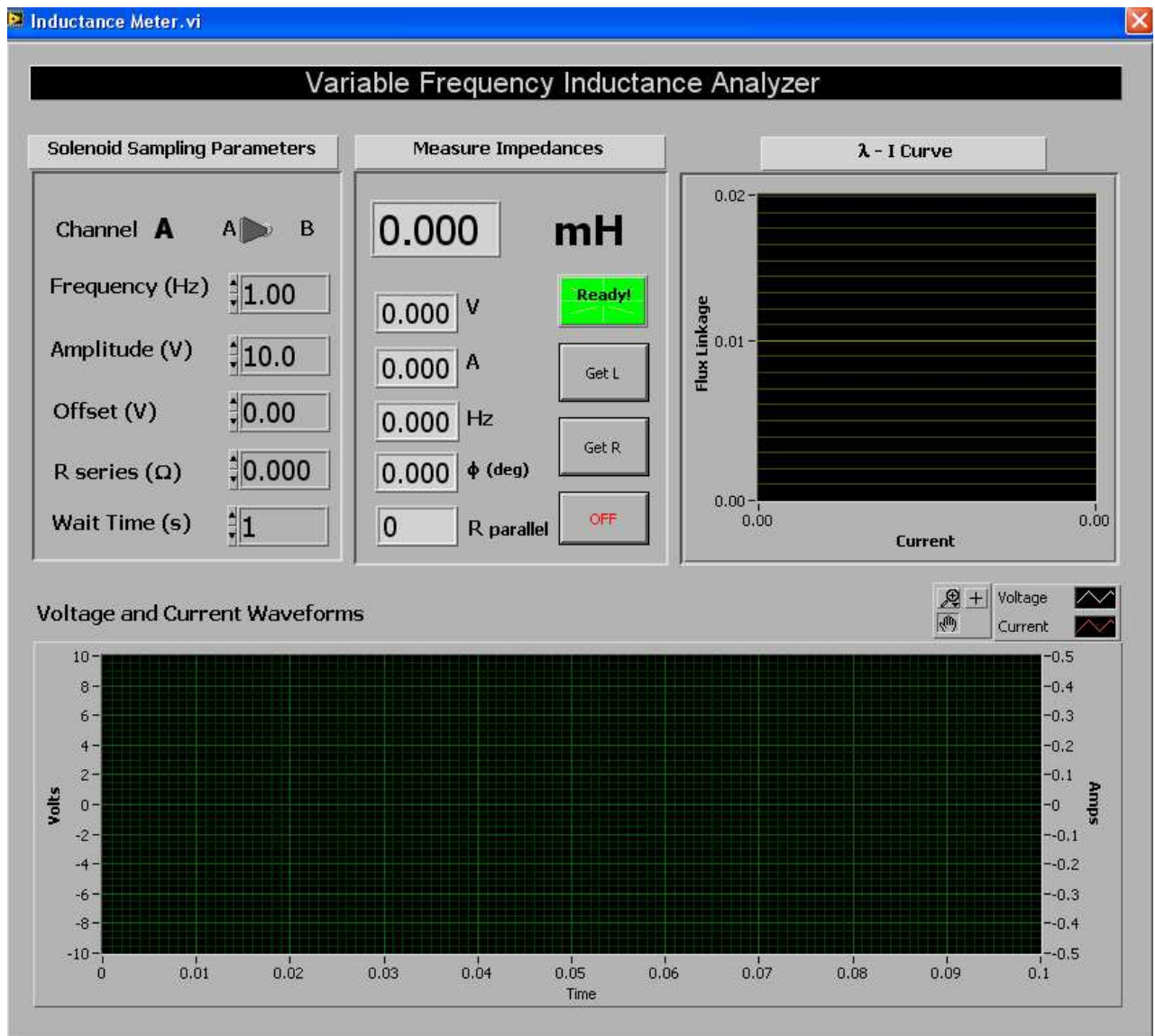


Figure 7: Inside Micrometer assembly.

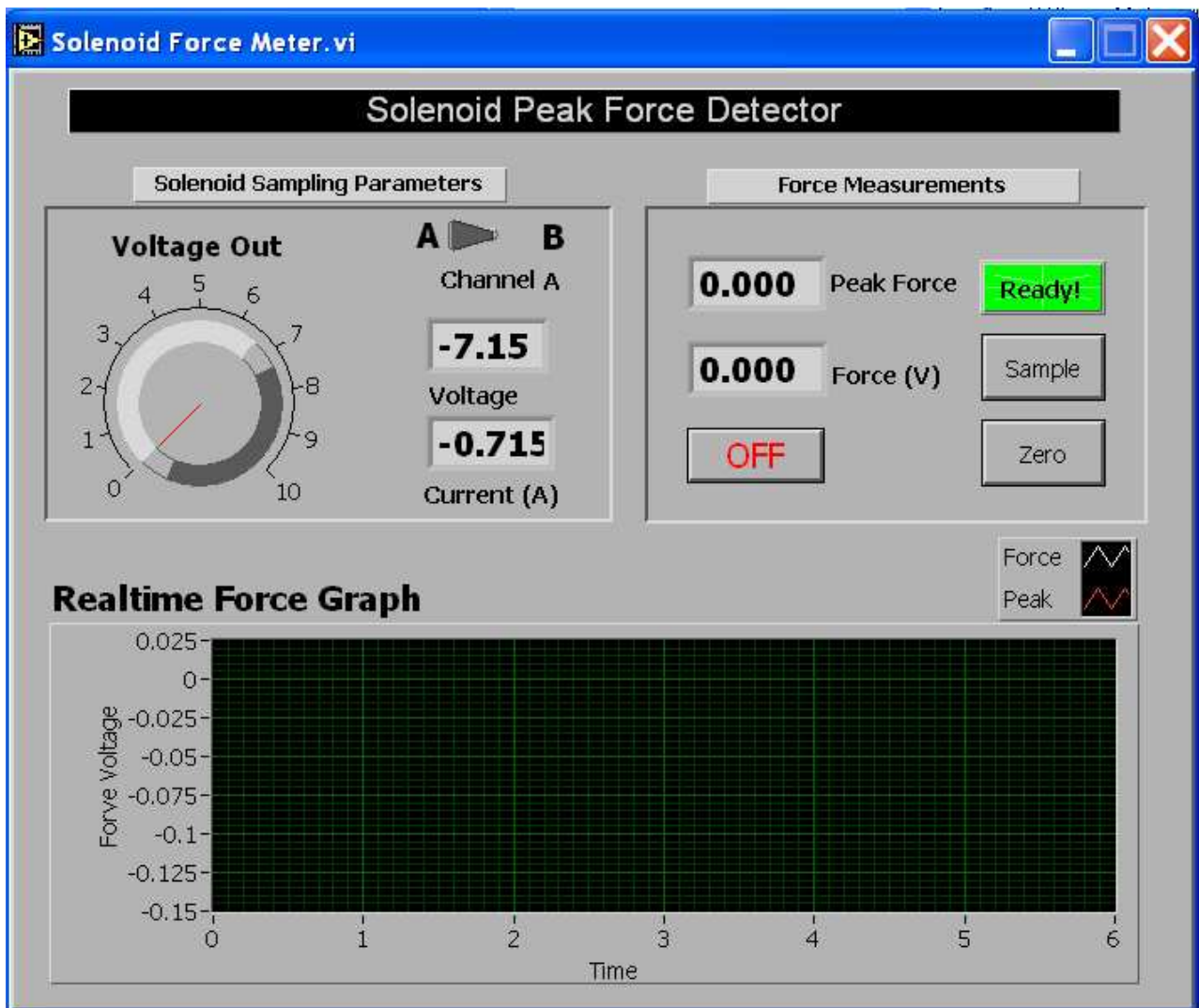
4.3 LabView Programs

There are three LabView programs which will be used during this lab experiment. These programs are found in the **LabView Programs** folder on the Desktop of your PC, or they may be downloaded from your course website. Alternatively, ask your TA to help you locate these programs:

Inductance Meter – This program is used to generate the inductance profile versus plunger position. This program also measures the DC resistance of the coil connected to one of the Channel A or B of the **Power Amplifier** box. The DC resistance (equivalent series resistance) must be always measured first and its value should remain displayed in appropriate window on the left side under **R_series (Ω)**. The program also calculates **R_parallel** which may be used to estimate the core losses at a given frequency.



Solenoid Force Meter – This interface is used to control the output of the **Power Amplifier** Channel A and to display the voltage (force) measured by the **Load Cell** assembly.



5 Experimental Part

Task 1: Inductance Measurement

The first part of the lab requires measuring the inductance of the solenoid winding as a function of the plunger position. Before measuring the inductance, it is necessary to measure the dc resistance of the winding first. This value will be used for more accurate calculation of inductance in the next step. Follow the following steps:

Task 1 A: Measuring the Solenoid Resistance

- 1) Open the LabView software program titled “**Inductance Meter.**”
- 2) Plug the solenoid winding into Channel A of the **Power Amplifier.**
- 3) To measure the dc resistance of the winding, click the button “Get R” on the **Inductance Meter** LabView control interface. This will output a steady dc voltage to the solenoid for 1 second. The solenoid resistance is then automatically calculated from the measured current and applied voltage and is displayed on the screen. Record this value in Table 1 of your Lab Report. The remaining part of Table 1 you will complete later during your calculations.

Task 1 B: Measuring the Solenoid Inductance vs. Plunger Position

- 1) Set the output voltage frequency to 3 Hz, and set the amplitude to the voltage listed on your particular **Solenoid**, or specified by your TA.
- 2) Move the **Micrometer** backwards (inside to the left) until the plunger is just seated in the solenoid and record the zero position.
- 3) Click the button “Get L” in the **Inductance Meter** LabView panel. The **Power Amplifier** will then output a 3 Hz sine wave to the solenoid. You should see the Indicator LED alternate Red and Blue for several seconds.
- 4) When the procedure is done, you will see both the current and voltage waveforms displayed on the **Inductance Meter** panel. The program uses the measured phase difference between the voltage and current signals to calculate the inductance. Record the inductance and plunger position in Table 2 of your Lab Report and/or your notebook. You may also find convenient to enter the measured data directly into a spreadsheet file. You will need this data for future calculations.
- 5) Use the micrometer to pull the plunger out about 0.05 mm at a time and repeat steps 2) through 4). Continue recording the inductance at increasing plunger positions until covering a span of approximately 5 – 8 mm. As the plunger is extracted, it is possible to take longer and longer step sizes between the measurements. Try to get a total of about 15 to 20 data points and record them in Table 2.
- 6) Completely remove the plunger and make one final inductance measurement. This will give you L_0 , the leakage inductance.

Task 2: Force Measurement

The goal of this task is to measure the force profile of the solenoid at a given current. This is done by performing several measurements of the holding force at different plunger positions. Each force measurement is performed by pulling on the Lever Arm (see Figure 4) until the plunger breaks free from the magnetic attraction. The Load Cell will sense an increasing tension in the String until the plunger is pulled loose. At this moment, the peak recorded tension corresponds to the holding force for a given applied current and plunger position. To measure the tension force, you will also need to calibrate the Load Cell output so that the measured voltage can be converted into needed force. Follow the following steps:

Task 2 A: Calibrating the Load Cell for the Force Measurement

- 1) Open the LabView program called “**Force Measurement**”.
- 2) Calibrate the Force Transducer by first pressing the “Zero” button on the **Force Measurement** control panel to eliminate the offset error. After this is done, place a Calibration Weight (Mass) on the load cell and record the resulting voltage in Table 3 of your Lab Report. Place the weight as close to the pulley wheel as possible. Repeat this for three different weights to compute the **averaged conversion coefficient**. You will use this information to calculate the conversion coefficient from Volts (V) to Newtons (N). Calculate this factor and record it in Table 3.

Task 2 B: Measuring the Static Friction Force

- 1) Move the plunger to the zero position. Set the output to 0 V. Press the button “Peak Detect” on the control panel. The software will now graph, in real time, the force (voltage) seen by the load cell and simultaneously keep track of the peak value.
- 2) Slowly pull on the Lever Arm to measure the force needed to pull the solenoid plunger with no current. This records the static friction. Complete Table 4 of your Lab Report. You will need to take this into account (subtract) when estimating the electro-magnetic force in Task 2 C. Reset the program for the next measurement.

Task 2 C: Measuring Holding Force vs. Plunger Position

- 1) The plunger should be in the zero position. Set the output voltage to the rated value for your solenoid and record the resulting current and voltage in Table 5 of your Lab Report.
- 2) Press the button “Peak Detect” on the control panel. The software will now graph in real time the force seen by the load cell and simultaneously keep track of the peak value.
- 3) Slowly pull on the Lever Arm with increasing force until the plunger comes free. Try not to yank or jerk the Lever Arm as this will produce an artificially high force peak.

- 4) Record in Table 5 the maximum load cell voltage and the plunger position.
- 5) Repeat steps 2) through 4) at increasing plunger distances until you have spanned 5 to 8 mm. Aim to get about 15 to 20 data points, with small steps near the sensitive zero position and larger steps further out. Record all the data points in Table 5 for future calculations. For convenience, you may record the measurements directly in a Spreadsheet file.

Task 2 D: Measuring Holding Force vs. Current

- 1) Set the plunger position to some small value, anywhere between 0.5 and 2 mm (say 1.0 or 1.2 mm). Record this value in Table 6 of your Lab Report.
- 2) Vary the applied voltage from 1 V to 10 V in several steps. Record the current through the solenoid and measure the corresponding holding force at each point. Record the data in Table 6 of your Lab Report. You will need this data to plot the measured and calculated force versus current characteristics.

6 Calculations and Analysis

The proper analysis of this lab requires least-squares fitting and is best done with either a mathematical software package e.g. Matlab, Mathematica, or a spreadsheet program such as Excel. You are free to use whatever method you are most comfortable with. An explanation of how you can do it using the MS Excel and Matlab is provided in Appendix for your reference.

Task 1: Solenoid Characterization

Assume that your solenoid can be described by equations (1) and (2). The parameters k_1 and k_2 should be established using a curve-fitting technique that minimizes the error between the measured and calculated inductances $L(x)_{measured}$ and $L(x)_{calc}$. Determine the parameters L_0 , k_1 , and k_2 , and record their values in Table 1 of your Lab Report. Assuming this step has been done; use these parameters with (1) and (2) as your solenoid model. On the same graph plot the measured inductance and the inductance calculated according to equation (1). Comment on your data fit.

Task 2: Force Analysis

Using the parameters from your solenoid characterization, calculate the predicted electromagnetic force profile of the solenoid using equation (2). Take the measured force values and subtract the component due to friction to determine the measured electromagnetic holding force $F_{e,measured}$. Complete Table 5 of your Lab Report. On the same graph plot the $F_{e,measured}$ data points along with the calculated force curve $F_{e,calc}$ and observe the level of agreement between the two sets of data.

Equation 2 also predicts that at a given position, the electromagnetic force of a reluctance device should increase proportional to the square of the current. Complete Table 6 of your Lab

Report with the results predicted by the calculations. Plot the measured electromagnetic force vs. applied current for the plunger position that you have considered. Does that graph show a quadratic relationship? Can you explain any observed deviations from this rule using your understanding of this real magnetic system?

Task 3: Additional Questions

In the summary of your report, provide the answers to the following questions:

- 1) What would be the effect of measuring the inductance at very high frequency vs. very low frequency?
- 2) What is the effect of saturation?
- 3) What can you say about the $\lambda - i$ loop obtained/observed during your measurements?
- 4) What happens when you very rapidly pull out the plunger from a solenoid that is connected to the dc source? Try to experiment with this during the lab. Provide brief observations and explanations.

7 Reporting

Prepare the Lab Report according to guidelines described on the class web page or in this manual. Your comments should be brief and to the point (no need to write long reports!). The Lab Report should include:

- 1) Title Page (all filled-in, with signatures)
- 2) Prelab signed by TA (if required)
- 3) Pages with the measured data (pages 14 to 17 with Tables 1 through 6)
- 4) Additional pages with calculations, discussions, plots, and/or answers to questions in Section 6,
- 5) Brief Conclusion/Summary stating what you and your lab partner have learned in this Lab.

8 Appendix

a) Using MS Excel

It is assumed that your solenoid can be described by equations (1) and (2) which include the parameters k_1 , k_2 and L_0 . The leakage inductance L_0 is assumed to be the inductance with the plunger removed. The parameters k_1 and k_2 can be obtained using a curve fitting technique known as the least-squares fitting. This method is based on determining what set of parameters produces the closest match with equation (1). The total error is equal to the sum of $(L_{measured} - L_{calc})^2$ for each point, and the best fit parameters are defined as those that minimize this error. An example of how this is done with excel is shown below:

	A	B	C	D
1	k ₁ =	2		
2	k ₂ =	1		
3	L ₀ =			
4	Err	4.50734		
5				
6	x	L meas	L(x)	err^2
7	0	2.1	3.00	0.81000
8	0.381	1.48	2.45	0.93746
9	1.016	1	1.99	0.98419
10	1.651	0.81	1.75	0.89195
11	2.921	0.57	1.51	0.88374

Figure 8: Data analysis using Excel

The cells in column **C** are based on equation (1) and produced from the following formula:

$$\text{Cell C7: } =\$B\$1/(\$B\$2+A7)+\$B\$3 \quad (3)$$

Column **D** is simply the squared difference between the calculated values in **C** and the measured values in **B**. For instance, $D8 = (B8 - C8)^2$. The values for k_1 and k_2 are simply guesses at this point, while the value **Err** is calculated as the sum of all the elements in column **D**. In this case $B4 = \text{SUM}(D7:D11)$

The optimum values for the parameters are found automatically using the excel **Solver** add-in. To ensure that **Solver** is installed, click on Tools -> Add-ins and check the box beside **Solver Add-In**.

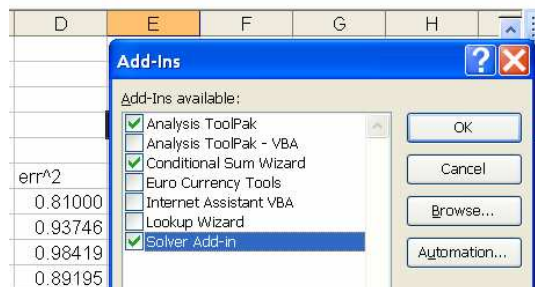


Figure 9: Solver Add-in

The solver will then appear in the Tools menu if it was not already there. Select Tools->Solver and the following block will appear. Set your **Target Cell** to the cell containing the sum of the errors. You want this to achieve a **Min** value by modifying the three cells containing your solenoid parameters.

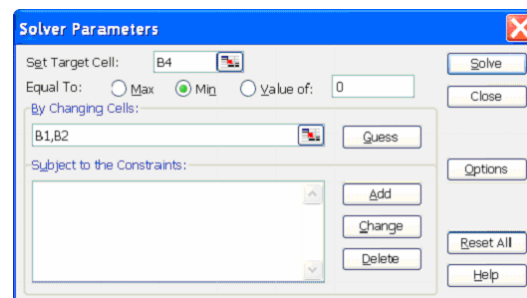


Figure 10: Excel Solver Parameters

Using the **Solver**, cells may be selected by simply clicking on them. Click on **Solve** and the solver will converge to a set of parameters that gives the minimum error. In this case, we see that the new values for k_1 and k_2 produce a calculated inductance that matches the measured values much more closely.

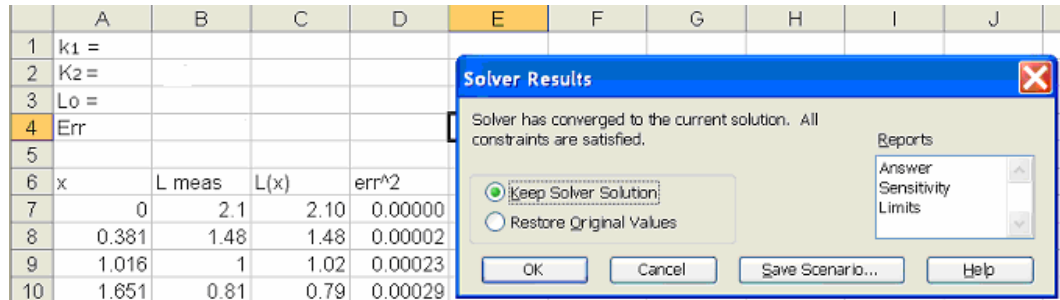


Figure 11: Solver Output.

After the **Solver** is ran, the cells are automatically updated with the optimum solution. Use these parameters determined for your solenoid and plot on the same graph the measured inductance and the inductance calculated according to equation (1). Comment on your data fit.

b) Using Matlab

Assuming the measured data L_0 and $L_{measured}(i)$, you can calculate the column vector of the measured magnetizing inductance as

$$L_{measured}(i) - L_0 = L_{m,meas}(i) \quad (4)$$

Based on equation (1), you also know that $L_{m,meas}(i) = \frac{k_1}{k_2 + x_{measured}(i)}$, for some unknown k_1 and k_2 . This can be re-written as

$$L_{m,meas}(i) \cdot k_2 + L_{m,meas}(i) \cdot x_{measured}(i) = k_1 \quad (5)$$

In matrix form, this can be put as $\mathbf{Ax} = \mathbf{b}$, where $\begin{bmatrix} 1 & -L_{m,meas} \\ \vdots & \vdots \end{bmatrix} \cdot \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} = \begin{bmatrix} L_{m,meas} \cdot x_{measured} \\ \vdots \end{bmatrix}$.

This is a least-square problem which has more equations than unknowns, and it can be solved very conveniently in Matlab environment using the back slash command as $\mathbf{x} = \mathbf{A} \setminus \mathbf{b}$.

EECE_____

Lab # ____

Section: ____

Bench #:

Partners	Student ID #:	% participation	Signatures

Date Performed:

Date Submitted:

Table 1: Solenoid Parameters

Measured solenoid dc resistance, r (Ω)	
Calculated L_0 (include units)	
Calculated k_1 (include units)	
Calculated k_2 (include units)	

Table 2: Measurement of the solenoid inductance vs. plunger position.

Measurement	1	2	3	4	5	6	7	8	9
Plunger Position, x (mm)									
Inductance, L (H)									
Measurement	10	11	12	13	14	15	16	17	18
Plunger Position, x (mm)									
Inductance, L (H)									
Measurement	19	20	21	22	23	24	25	26	27
Plunger Position, x (mm)									
Inductance, L (H)									

Table 3: Load Cell calibration

Measurement	1	2	3
Weight mass, g			
Voltage			
Averaged conversion coefficient $C_{VN} = \frac{\text{Force(Weight)}}{\text{Voltage}}$			

Table 4: Measured Friction Force

Recorded Voltage, V	Force, F_{fric} , (N)

Table 5: Force vs. Plunger Position Characteristic

Measured				Calculated
Voltage applied to the solenoid is =				
DC current through the solenoid is =				
Position, $x, (mm)$	Load Cell voltage, $V_{cell}, (V)$	Total measured force, $F_{total}, (N)$	Measured electromagnetic force, $F_{e, meas}, (N)$	Electromagnetic force calculated by your model, $F_{e, calc}, (N)$

Table 6: Force vs. Current Characteristic

Measured				Calculated
Plunger position, $x =$				
Applied voltage, $V, (V)$	Solenoid current, $I, (A)$	Load Cell voltage, $V_{cell}, (V)$	Measured electromagnetic force (subtract friction), $F_{e,mes}, (N)$	Electromagnetic force calculated by your model, $F_{e,calc}, (N)$